ISSN 0038-0946, Solar System Research, 2015, Vol. 49, No. 7, pp. 573–579. © Pleiades Publishing, Inc., 2015.
Original Russian Text © N.S. Kardashev, A.V. Alakoz, Y.Y. Kovalev, M.V. Popov, A.M. Sobolev, K.V. Sokolovsky, 2014, published in Vestnik "NPO imeni S.A. Lavochkina", 2014, No. 3, pp. 4–11.

Radioastron: Main Results of the Implementation of the Early Science Program in Studies of Astronomical Objects in the Universe with Ultra-High Angular Resolution

N. S. Kardashev[a], A. V. Alakoz[a], Y. Y. Kovalev[a], M. V. Popov[a], A. M. Sobolev[b], and K. V. Sokolovsky[a]

[a]*Astro Space Center of Lebedev Physical Institute of the Russian Academy of Sciences, Profsoyuznaya ul. 84/32, Moscow, 117997 Russia*

[b]*B.N. Yeltsin Ural Federal University, ul. Mira, Yekaterinburg, 620002 Russia*

e-mail: nkardash@asc.rssi.ru; rett@asc.rssi.ru; yyk@asc.rssi.ru; asc.rssi.ru; Sobolev@urfu.ru; kirx@scan.sai.msu.ru

Received May, 14, 2014

Abstract—The paper presents the main results of the implementation of the Radioastron Early Science Program. Interferometric responses (fringes) were obtained for all types of studied radio sources (quasars, pulsars and cosmic masers) and in all ranges of wavelengths (from meter to centimeter range) with large space-ground baselines. Such measurements have provided a record angular resolution, in some cases reaching several tens of microseconds of arc. This brings unique scientific results concerning the nature of the processes occurring in the vicinity of the supermassive black holes, the structure of the interstellar plasma inhomogeneities and dynamics of compact objects in star-forming regions.

Keywords: space-ground interferometer, Very Long Baseline Interferometry (VLBI), active galactic nuclei (AGN), quasars, pulsars, cosmic masers

DOI: 10.1134/S0038094615070096

INTRODUCTION

In 2011, the Radioastron, which is a unique observatory nearly the size of the Earth-to-Moon distance, integrating a 10-meter Russian space radio telescope and the largest world land telescopes in the united space-ground interferometer, was successfully put into operation. The project is created by order of the Russian Academy of Sciences within the Russian Space Program. The head developer of the project is Lavochkin Scientific Production Association, the head scientific organization is the Astro Space Center of the Lebedev Physical Institute of the Russian Academy of Sciences. Many technical solutions realized on the spacecraft are innovative and unique. As the experts in Russia and abroad note, this extremely successful project defines today the world level of radio-astronomical observations from space.

The space radio telescope (SRT) is established on the specialized SPEKTR-R satellite. It operates in four radio wave bands, 1.2–1.6, 6.2, 18, and 92 cm, in two polarizing channels with right and left circular polarization. The signals from space radiation sources received by SRT are transformed into a digital form and are transmitted in real time to the scientific data reception stations of (Pushchino near Moscow and Green Bank in the US) by radio link with a bandwidth of 144 Mbps. Synchronization of signals and of frequency transformations on board the satellite are carried out from an onboard hydrogen frequency standard. In the control, tracking, reception and transmission of information a number of ground objects take part: the Flight-Control Center (FCC) of the Lavochkin Scientific Production Association; the Deep Space Network communication antennas in Ussuriisk and in Medvezh'i Ozera, used for control by satellite, (command transmission and telemetry reception); the reception stations for scientific data in Pushchino (Lebedev Physical Institute of the Russian Academy of Sciences) and in the Green Bank National observatory in the US; the laser ranging stations and the terrestrial radio telescopes taking part in observations.

The "Quasar" being the Russian geodesic radio interferometric network of the Institute of Applied Astronomy in St. Petersburg gives significant support to the Radioastron project by carrying out the joint observations with the space telescope at the three 32-meter radio telescopes of institute. The final stages of preparation of the project are described in our magazine in N.S. Kardashev's article with co-authors (Yu.A. Aleksandrov et al., 2011), the results of flight tests are presented in publications (V. Yu. Avdeev et al., 2012; N.S. Kardashev et al., 2013), and the realized parameters of the space-ground interferometer are given in the work (Y.Y. Kovalev et al., 2015). In 2014, the special issue of the "Space Research" magazine was prepared describing the technical details concerning an onboard scientific complex, and the features of mission control and the questions of flight support.

The Astro Space Center (ASC) of the Lebedev Physical institute carries out the scientific program of the Radioastron observatory. Functioning of the SPEKTR-R satellite is supported by the "Roskosmos" Russian Space Agency and performed by the Lavochkin Scientific Production Association. The ballistic group of Keldysh Institute of Applied Mathematics in Moscow carries out the measurements for orbit determination and the analysis of these data. Scientific data from the space radio telescope, receiving by tracking stations, are recorded in the RadioAstron Data Format (RDF) developed specially for this project. Correlation of data is carried out on the correlator of ASC. In addition, the correlation of data is partially carried out on the correlator of the Max Planck Institute for Radio Astronomy (MPIfR) in Bonn (Germany) and on the correlator of the Joint Institute for VLBI in Europe (JIVE) in Dwingeloo (the Netherlands).

In this publication, we provide some preliminary results of the implementation of the early scientific program (ESP) of the Radioastron project by international scientific groups on the study of nuclei of active galaxies, pulsars, the interstellar medium and masers. Scientific groups will publish the full results of the ESP in a series of separate articles.

1. SCIENTIFIC PROGRAM

The main object of the project is the following: by means of the space telescope, operating together with ground telescopes by an interferometer principle, to achieve previously unachievable spatial resolution at certain wavelengths and to provide a new quality of scientific data in a radio frequency band. In particular, it has become possible to measure the sizes and construct the radio images of those objects, which had appeared as points. It is possible to study the fine structure of material jets, with a high speed fluxing of the centers of active galactic in the neighborhood of supermassive black holes. An important task is the measurement of the brightness temperature in the region of radio emission generation. On the properties of the radio emission received by the interferometer one can also study the space plasma that is the material of the interstellar medium, which accordingly distorts the radio signal coming from the most compact sources of radiation—pulsars. A separate task consists in studying the kinematics and dynamics of compact sources of line radio emission of masers in star formation regions.

Implementation of the Radioastron mission started with the flight tests, of which the engineering tests of the spacecraft main systems were the first part. Then, the opening of a radio telescope mirror was carried out, activation of devices on board the scientific complex and testing of the whole scientific complex in an independent mode by radiation reception from calibration radiation sources. These tests took about three months, and in November, 2011, the tests were begun in an interferometric mode involving the largest radio telescopes in the world. The first interferometric observations appeared successful. Tests proceeded until May, 2012, in all frequency ranges and all measurement modes (the sources being continuous spectra, radio lines and pulsars) were tested. Further, the implementation of the scientific program was started.

Implementation of the scientific program in the Radioastron project is divided into three stages: the early scientific program (ESP), the key scientific program (KSP) and the general scientific program (GSP). The early scientific program was carried out by participants in the project and the organizations provided their large ground radio telescopes as a ground arm of the interferometer. ESP began in February, 2012, and proceeded until the end of June, 2013. For implementation of the ESP, three scientific groups on extragalactic radiation sources, on pulsars and on the maser sources radiating in the radio lines of hydroxyl and water vapor molecules were created. Participants of these working groups selected the most promising objects of research, ordered the necessary observation time on the ground radio telescopes according to competitive demands, drew up the observation program and analyzed the results from a correlator output. The ESP was aimed at receiving the first scientific results and on ensuring measurement of the basic parameters of the space-ground interferometer. In the ESP, the analysis of features and functional restrictions for providing this information for potential participants of the basic scientific program, which was the following stage of implementation of the program of scientific study in the Radioastron project was carried out.

During the ESP, first, it was confirmed that the space-ground interferometer operates and provides data with the record angular resolution at short wavelengths (1.35 cm, 22 GHz), that is, at ten and more times better than is possible using only ground telescopes. Besides, interesting results for separate objects of the program were received.

The KSP started on July 1, 2013. It was drawn up based on competitive consideration of scientific demands from the Russian and foreign research teams. For an assessment of applications, the Radioastron Program Evaluation Committee (RPEC) was created, which included authoritative experts from Australia, Germany, the US and Russia. Thirteen collective demands from about 200 researchers from 19 countries (Russia, the US, Germany, Australia, Italy, the Netherlands, Great Britain, Ukraine, Spain, Japan, South Korea, South Africa, Canada, Poland, China, Hungary, Mexico, India and Greece) came in. The RPEC approved seven scientific applications, which formed the content of the KSP for the period from

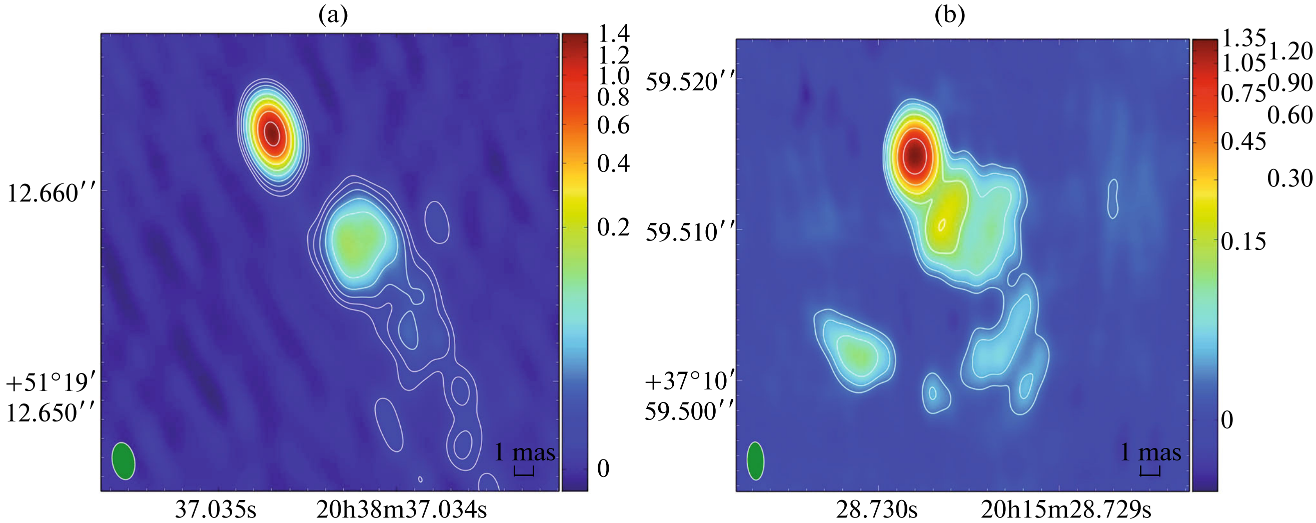

Fig. 1. The results of the mapping of 2013+370 (a) and 3C 418 (b) quasars at the wavelength of 6.2 cm.

July, 2013, to June, 2014. The third stage of the program of scientific research represents the balance between new applications of the KSP and GSP. It started in July, 2014.

2. MAIN RESULTS OF THE STUDIES OF THE EARLY SCIENTIFIC PROGRAM

Within the framework of implementation of the Radioastron mission scientific program, three groups of space objects were studied. There were quasars, the nuclei of distant galaxies, pulsars, the neutron stars of our galaxy, and space masers in the water and hydroxyl radio lines, being observed in the region of formations of star and planets and shells of stars of late spectral classes in our galaxy, and also in regions of star formation and circumnuclear disks of other galaxies.

The radio telescopes of Russia, Ukraine, Australia, Great Britain, Germany, India, Spain, Italy, the Netherlands, Poland, Sweden, China, the Republic of South Africa, the US, Japan et al., participated in the observations. Current information on a state of the project and scientific results is available on the Radioastron mission website (http://www.asc.rssi.ru/radioastron/news/news.html).

Using the space interferometer, about one thousand of observation sessions were carried out involving the largest radio telescopes worldwide. Interference studies were carried out for more than 100 quasars and radio galaxies, 20 pulsars and 15 space masers.

By means of the Radioastron project, it was possible to break the world records on angular resolutions, having realized the keenest eye in the history of scientific experiments on our planet. The signals from many distant space objects are reliably recorded on the baseline of the ground-space interferometer of up to 250 thousand kilometers. For the first time in scientific practice, the interferometer scheme with projections of bases of such length is realized and with the successful detection of radiation from ultra-compact areas of cosmic objects, namely: 20 Earth diameters (the study of pulsars at a wave length of 92 cm); 27, 22, and 15 Earth diameters (the study of quasars at wave lengths of 18, 6.2, and 1.3 cm); 5 Earth diameters (the study of masers at a wave length of 1.3 cm).

Thus, the ground-space interferometer operating at wavelengths from 92 to 1.3 cm is realized, and the record angular resolution in 27 μas is achieved in the observation of one of the quasars.

2.1. Studies of Active Galactic Nuclei

From the observations of quasars at distances of billions of light years from the Earth, it is possible to obtain detailed images of ejections of hot material (jets) and measure the width of a nozzle of ejections near the central supermassive black hole. From the Radioastron and telescopes of the European VLBI-network data, the first ground-space radio images of active galaxies were constructed. The image of 0716+714 Lacertidae is presented in the article of N.S. Kardashev et al., 2013, and 3C 418 and 2013+370 maps are shown in Fig. 1; these images are constructed in a range of wavelengths of 6.2 cm. In the observation of 2013+370 and 3C 418, together with a space radio telescope, the European VLBI network participated, as well as telescopes outside the network sited in Evpatoria (Crimea) and Usuda (Japan). The experiment was carried out on October 31, 2012. On the horizontal axis, shown in Fig. 1, the right ascension was indicated, the declination is indicated on the vertical axis; the color scale specifies the color concordance of the measured flux density in terms of Jansky/solid angle of the synthesized beam. The ellipse in the bottom left corner of the images shows a section of half the intensity of the synthesized directional pattern of the space interferometer.

In all three cases, owing to the space interferometer, it succeeded in reliably resolving the jets in the transverse direction and measuring the width of their visible bases. The width of a nozzle of 0716+714 was estimated at about 70 μas, which corresponds to 0.3 parsec (about 10 trillion km). For 2013+370 and 3C 418 the width of the visible basis of the jet was 160 and 500 μas (1.2 and 4.3 parsec) respectively. These results are extremely important for studying the question of the formation and collimation of jets in quasars. The estimated brightness temperature of the bases of jets in all three objects (some trillions of K) correspond to the radiation model of relativistic electrons with Doppler amplification. It was supposed that just electrons are responsible for radiation from jets in active galactic nuclei. However, to explain the results of observations in the context of this model, the ejection speed should be several times more than was supposed earlier.

The study of the brightness of quasar nuclei was the basic EPS project of Radioastron. Ground VLBI experiments are not sensitive to extreme values of brightness (Y.Y. Kovalev et al., 2005). Only the ground-space interferometer with large bases (the distance between two telescopes participating in the interferometric observations) allows testing the existence of, or lack of, very hot spots in active galactic nuclei. At wavelengths of 18 and 6.2 cm, the interferometer succeeded in recording the radiation of many compact galactic nuclei on the Radioastron base up to 20 Earth diameters. These galaxies are the following, 3C 273, 3C 279, OJ 287, BL Lac, 0529+483, 1642+690 and tens of others. Positive measurements with detection at record base lengths were obtained generally with the most sensitive ground telescopes: in Effelsberg (Germany), in Arecibo and GBT (United States). In the same time, we note that all ground radio telescopes participating in the observations regularly show positive measurements with SRT.

On the shortest wavelength of 1.3 cm, as already mentioned above, the record results were received with the GBT and VLA telescopes (United States) on projections of the interferometer base up to 8 Earth diameters. The total quantity of independent measurements (experiments), in which values from active galactic nuclei were obtained from the extreme ground-space bases of interferometer, was about 30%. First results of the Radioastron survey of active galactic nuclei are presented in proceedings of the European VLBI network symposium (K.V. Sokolovsky et al., 2013).

The main conclusion of the survey can be formulated as follows. The nozzles of jets in active galaxies appear much hotter than considered earlier. It leads to a qualitative change of understanding of the radiative mechanism of relativistic ejections of quasars. The following options for an explanation of this unexpected result are proposed: the radiation of relativistic protons, much greater than previously thought, the Doppler boosting of emission, coherent synchrotron radiation and the continuous acceleration of particles in an apparent jet nozzle. Thus, these results challenge both of the nature of synchrotron radiation of jets in quasars, and understanding of properties of the interstellar medium.

2.2. Studies of Pulsars and the Interstellar Medium

During the studies of radio emission from pulsars using the Radioastron ground-space interferometer, the interferometric responses are received at frequencies of 1660 and 324 MHz at all values of interferometer base lengths up to maximum of 240000 km (20 Earth diameters). It is evidence that neither the influence of ionospheric fluctuations, nor the scattering effect on inhomogeneities of the interstellar plasma completely blur the image. The observations of the pulsars, having such small physical sizes that for telescopes they remain point sources, are important not only for understanding the processes in pulsars, but also for studying the parameters of the interstellar medium.

For the PSR B0950+08 pulsar receives information on the distribution of the interstellar plasma along the line of sight, which scatters a signal and causes it to flicker. The ground and space telescopes formed the interferometer with a base of 220000 km, which allowed achieving a record resolution in the VHF range. Fluctuations of a signal look like modulation at a level of about 40%. It has been shown that such a modulation one could result in the plasma configuration along a line of sight in the form of two scattering layers and “a space prism” with a sufficiently abrupt gradient in distribution, deflecting a radio emission over angles of 1.1–4.4 mas. The distant scattering layer is, most likely, on the external boundary of the Local Bubble (the region of the rarefied gas in the galactic arm) at distances of 26–170 parsec, and the near layer (4.4–16.4 parsec) is on the ionized surface of a molecular cloud. The spectrum of turbulent fluctuations of density in both layers follows a power law with indices of $\gamma_1 = \gamma_2 = 3.00 \pm 0.08$ that differs from a Kolmogorov spectrum with $\gamma = 11/3$. These results could not be obtained with observations only from Earth’s surface since the Fresnel zone for the refraction of radiation of a pulsar exceeds the Earth’s diameter. The results of this research were published in the leading international astronomical magazine, Astrophysical Journal (T.V. Smirnova et al., 2014).

For the B0329+54 pulsar it was found the refractive image shift was caused by moving ionospheric perturbations. For this pulsar, the half-width of spot of confusion which was found equal to 4 mas at half-width.

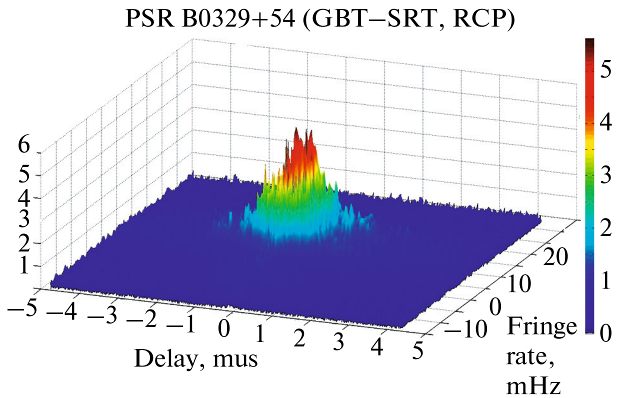

Fig. 2. Multicomponent image of PSR B0329+54 pulsar on the observations at a wavelength of 92 cm.

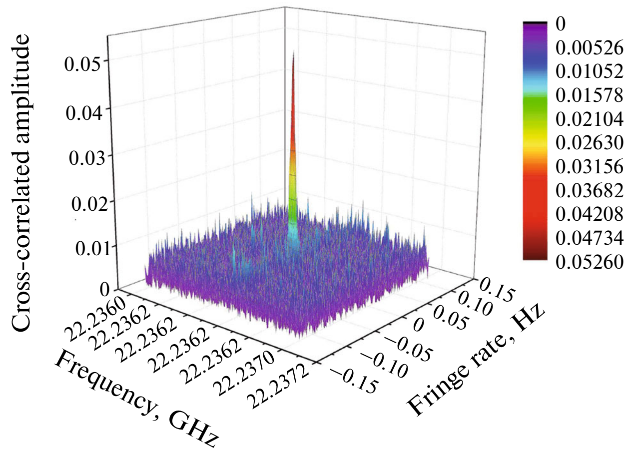

Fig. 3. Interferometric response to the water maser emission from the star-forming region W3 IRS5.

Figure 2 shows the multicomponent structure of the interferometer response for the B0329+54 pulsar, obtained at the projection of the base of the ground-space interferometer on the picture plane of a pulsar at 100000 km, (on the ground bases such response looks like the single narrow isolated maximum). On one horizontal axis in Fig. 2, the values of delay in the time interval from −5 to +5 μs are indicated; on the other horizontal axis, the values of residual frequency interference from −15 to +25 MHz are indicated, and on a vertical axis the amplitude of the visibility function in percentages is given.

For a pulsar in the Vela constellation, which demonstrates the strongest scattering among studied objects, the amplitude and shape of the correlation function on the ground-space bases is also multicomponent and does not correspond to the predictions of the existing theory of radio wave propagation through the inhomogeneities of the interstellar plasma, and this theory needs corrections.

The observation results of all other pulsars in the project have been successful, mysterious and contrary to the predictions of the interstellar medium theory. It was believed that the scattering effects in a galaxy on the path from the pulsar to Earth would hamper to such a high resolution. The results received by Radioastron represent an opportunity for studying the interstellar plasma turbulence, moreover, they compel scientists to revise fundamentally the structure of compact turbulent bunches of scattering screens.

The existing interpretations of the effects of radio wave propagation through heterogeneous interstellar plasma in our galaxy predicted that long-wave radiation from pulsars and quasars will be blurred, and as a result, the Radioastron will not be able to record the signals from them on large ground-space bases for wavelengths of 18 and 92 cm. The results refute this prediction. This discovery can fundamentally change our understanding of the structure of turbulent clumps of interstellar plasma in our galaxy.

2.3. The Studies of Galactic Maser Radiation Sources

Within the framework of the scientific program for the investigation of space masers using the Radioastron ground-space interferometer, fifteen maser emission sources were observed in the lines of hydroxyl (with rest frequencies at 1665.4018 and 1667.3079 MHz) and water (22235.08 MHz) molecules. Masers are extremely compact objects and they are often not resolved even on the largest ground bases having the highest brightness temperature up to 10^{14} K. Owing to these properties, using these one can study the kinematics and physical parameters of objects in our and other galaxies with high accuracy. Observations on the ground-space interferometer allow not only investigation of the movements in the very distant objects, but also to resolve the most compact parts and to evaluate the brightness temperature of a maser source and its size, which is necessary to understand the pumping mechanism and to build the model of the radiating region.

During the studies carried out, emission from very compact maser features was detected in the direction of six regions of star formation: W3 IRS5, W51 M/S, Cepheus A and Orion A in the water line at frequency of 22 GHz, as well as W75N and Onsala 1 in the hydroxyl lines at a frequency of 1.6 GHz.

Observation of maser radiation at the water line from the W3 IRS5 region of massive star formation, located at the distance of 1.8 kpc in the spiral arm of Perseus in our galaxy, the maximum projections of the space interferometer base, on which the signal was detected, amounted to 5.28 and 5.42 Earth diameters (about 69000 km), providing the highest angular resolution (about 40 μas) ever obtained in the studies of cosmic masers. Figure 3 shows an example of the response to the water maser radiation in the region of

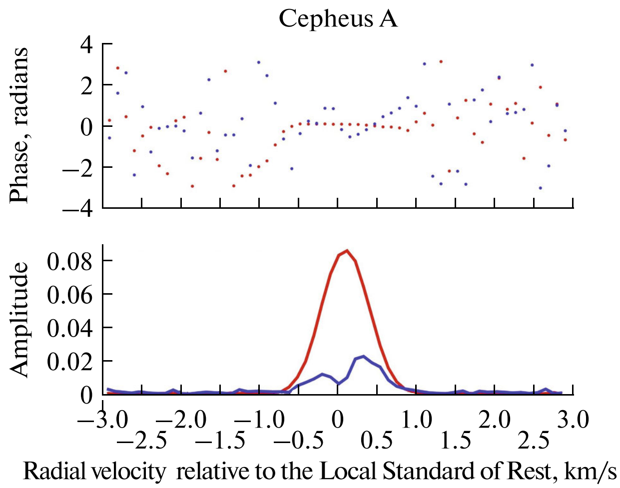

Fig. 4. Comparison of the cross-correlation spectra of compact detail in the Cepheus A star-forming region.

W3 IRS5 star formation, obtained on the base of the space radio telescope—the ground telescope in Torun (Poland), with the base projection of 5.28 Earth diameters. The frequency of the observed signal in the geocentric system and the value of the residual interference frequency (Hz) are indicated on the horizontal axis; the amplitude of the correlated signal normalized to unity are indicated on the vertical axis.

Owing to the accompanying observations on VERA Japanese ground interferometer, the details observed on the ground-space interferometer had been associated with compact objects radiating in the radio and infrared continuum (H. Imai, private comm).

In the Cepheus A star formation region located at a distance of about 720 pc from the Sun, the emission was detected from the variable components of a water maser with an angular resolution of approximately 60 μas (the projection of the interferometer base during observations was about 3.5 Earth diameters), which corresponds to a linear resolution of about 6.5 million km. Figure 4 shows the comparison of the cross-correlation spectra of the compact maser detail in Cepheus A star formation region detected at the ground (red color) and-ground-space arm (blue color) of the interferometer with a base projection of 0.24 and 3.5 Earth diameters, respectively. The amplitude of correlated signal normalized to unity and the phase in radians, depending on the radial velocity relative to the Local Standard of Rest, are indicated on the axes. For clarity, the amplitude of the ground-space arm is scaled up. The dual detail structure shown on ground- and space-based, indicates the existence of two compact objects with sizes of the order of 10 μas. Thus, the objects are moving with large relative velocity. This means that the maser source has a complex spatial and kinematic hyperfine structure on the scales comparable with the size of our Sun. This picture is a possible indication that the maser radiation in this case occurs in protostellar or protoplanetary disks or turbulence cells of the smallest size corresponding to the dissipation scale.

The use of Radioastron for the first time provides the angular resolution sufficient to study important astrophysical objects forming a basis of our knowledge about the structure and evolution of the interstellar medium, as well as the formation of stars and planets.

For Onsala 1 object, the observations of hydroxyl masers (1665 MHz) also gave quite an unexpected result. This source, like most star formation areas, lies in the galactic plane, where the interstellar scattering is strongest. Therefore, the observed image, according to existing conceptions, should be very blurred. We succeeded to obtain a signal on the projection of the bases of about 24000 km, which corresponds to an angular resolution of 1.5 mas.Taking into account the successful observations of the other hydroxyl maser, W75N, as well as earlier observations of G34.26+0.15 and W48 on VSOP Japanese satellite (V.I. Slysh et al., 2002), one can say that, as in the case of the above observations of pulsars and quasars, our understanding of the properties of interstellar scattering material requires substantial revision.

The total percentage of successful detection is about 25%. All sources currently recorded were related to the region of massive star formation. In most sources, with ground-space bases several compact details are observed, which allow the investigation of the relative movements of the components.

CONCLUSIONS

(1) The ground-space radio interferometer providing the record angular resolution in four frequency bands (from 0.3 to 25 GHz) was implemented. During the project realization, many technical tasks were first solved: the largest space antenna with highly accurate surface 10 m in diameter with an automatic deployment in space was made from composite materials; for the first time in space, a hydrogen frequency standard of Russian production was installed on board the Spektr-R satellite; and transmission of scientific data on a broadband communication line (144 Mbps) with an operating distance up to 350000 km was successfully implemented.

(2) The survey of compact extragalactic radio sources (active galactic nuclei and quasars) found objects, the brightness temperature of which significantly exceeds the Compton limit, this resulted in a change of our understanding of emission mechanism of quasar cores.

(3) The data of Radioastron can restore the images of jets of emissions of relativistic plasma in active galaxies and measure the width of the nozzles of jets. These data are important for the study of formation and collimation of relativistic jets in active galactic nuclei.

(4) The characteristics of distribution of the plasma inhomogeneities were studied using the interstellar

plasma probing method by pulsar radio pulses: in the direction of the nearby PSR B0950+08 pulsar, two scattering layers were discovered at distances of about 10 and 100 pc from the Sun and in the direction to the brightest PSR B0329+54 pulsar in the northern hemisphere of the celestial sphere, an estimate of the upper boundary of the spectrum inhomogeneities of 5×10^{12} cm was proved.

(5) Vela, being the brightest pulsar in the southern hemisphere (constellation of Vela), demonstrated an abnormal intensification of coherence functions measured by the ground-space interferometer. Thus, the amplitude and shape of the correlation function at the ground-space bases do not agree with the predictions of the existing theory of propagation through the inhomogeneities of the interstellar plasma, and this theory needs clarification.

(6) Analysis of the results of interferometry of maser radiation sources in the regions of star formation indicates the existence of hyperfine spatial structure of compact details and, in the some cases, indicates the existence of a large velocity gradient in the studied region of star formation, about an order of magnitude greater than previously known values. This situation is possible in the central parts of the turbulent cells and protostellar or protoplanetary disks.

(7) Interstellar scattering does not prevent us from observing the masers in the galactic plane, even at the hydroxyl line frequencies (1.66 GHz) and even at bases significantly exceeding the Earth's diameter. This is in contradiction to the predictions of the modern theory of scattering and shows either a nonuniform distribution of scattering material, or a need for clarification of the theory itself (see above, item 5 and text about observations of pulsars and quasars).

ACKNOWLEGMENTS

The RadioAstron project is led by the Astro Space Center of the Lebedev Physical Institute of the Russian Academy of Sciences and the Lavochkin Scientific and Production Association under a contract with the Russian Federal Space Agency, in collaboration with partner organizations in Russia and other countries. The results presented are based in part on the observations made on radio telescopes of IAA RAS (Institute of Applied Astronomy, Russian Academy of Sciences). These studies are based in part on the Evpatoria RT-70 radio telescope (Ukraine) observations carried out by the Institute of Radio Astronomy of the National Academy of Sciences of Ukraine under a contract with the State Space Agency of Ukraine and by the National Space Facilities Control and Test Center with technical support by Astro Space Center of Lebedev Physical Institute, Russian Academy of Sciences. The obtained results are also based on the observations carried out at the 100-meter radio telescope of the Max Planck Institute for Radio Astronomy in Effelsberg (Germany), and on the participation of the European VLBI Network, comprising national tools in Europe, China and South Africa.

Other radio telescopes supporting the Radioastron interferometer were those of the National Radio Astronomy Observatory, USA, which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The Arecibo Observatory is operated by SRI International under a cooperative agreement with the National Science Foundation (AST-1100968), and in alliance with Ana G. Mendez-Universidad Metropolitana, and the Universities Space Research Association. The Australia Telescope Compact Array, Parkes and Mopra radio telescope, Long Baseline Array are part of the Australia Telescope National Facility which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

This work is partially supported by the Russian Foundation for Basic Research grants 12-02-12 103 and 13-02-00 460. Yu.Yu. Kovalev was partially supported by Dynasty foundation.

REFERENCES

Aleksandrov, Yu.A., Andreyanov, V.V., Babakin, N.G., Babyshkin, V.E., et al., Radiotelescope RADIOASTRON (SPEKTR-R project) is much larger than the Earth, *Vestn. Federal. Gos. Unitarn. Predpriyat. Nauch.-Proizv. Ob"ed. im. S.A. Lavochkina*, 2011, no. 3, pp. 11–18.

Avdeev, V.Yu., Alakoz, A.V., Aleksandrov, Yu.A., Andreyanov, V.V., et al., RADIOASTRON space mission. First results, *Vestn. Federal. Gos. Unitarn. Predpriyat. Nauch.-Proizv. Ob"ed. im. S.A. Lavochkina*, 2012, no. 3, pp. 4–21.

Kardashev, N.S., Khartov, V.V., Abramov, V.V., Avdeev, V.Yu., et al., "RadioAstron"—a telescope with a size of 300000 km: main parameters and first observational results, *Astron. Rep.*, 2013, vol. 57, no. 3, p. 154.

Kovalev, Y.Y., Kellermann, K.I., Lister, M.L., Homan, D.C., et al., Sub-milliarcsecond imaging of quasars and active galactic nuclei. IV. Fine-scale structure, *Astron. J.*, 2005, vol. 130, pp. 2473–2505.

Kovalev, Y.Y., et al., Space VLBI mission RadioAstron: first interferometric fringes, *Astron. Astrophys.*, 2015.

Slysh, V.I., et al., Space-VLBI observations of OH masers, *Proc. 206th IAU Symp. Cosmic Masers: from Proto-Stars to Black Holes, held March 5–10, 2001 in Angra dos Reis, Rio de Janeiro, Brazil*, Migenes, V. and Reid, M., Eds., San Francisco: Astronomical Society of the Pacific, 2002, p. 105.

Smirnova, T.V., Shishov, V.I., Popov, M.V., Gwinn, C.R., et al., Studies of the nearby, turbulent interstellar plasma with the longest radioastron space-ground interferometer baseline, *Astrophys. J.*, 2014, vol. 786, no. 2, pp. 115–129.

Sokolovsky, K.V., et al., Radioastron early science program. space-VLBI AGN survey: strategy and first results, *Proc. 11th EVN Science Symp.*, Bordeaux, 2012, pp. 1–6.

Translated by M. Kromin